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(54) **VOLTAGE LIMITING BIAS CIRCUIT FOR
REDUCTION OF HOT ELECTRON
DEGRADATION EFFECTS IN MOS
CASCODE CIRCUITS**

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(58) Field of Search 330/277, 288,
330/307, 311, 296

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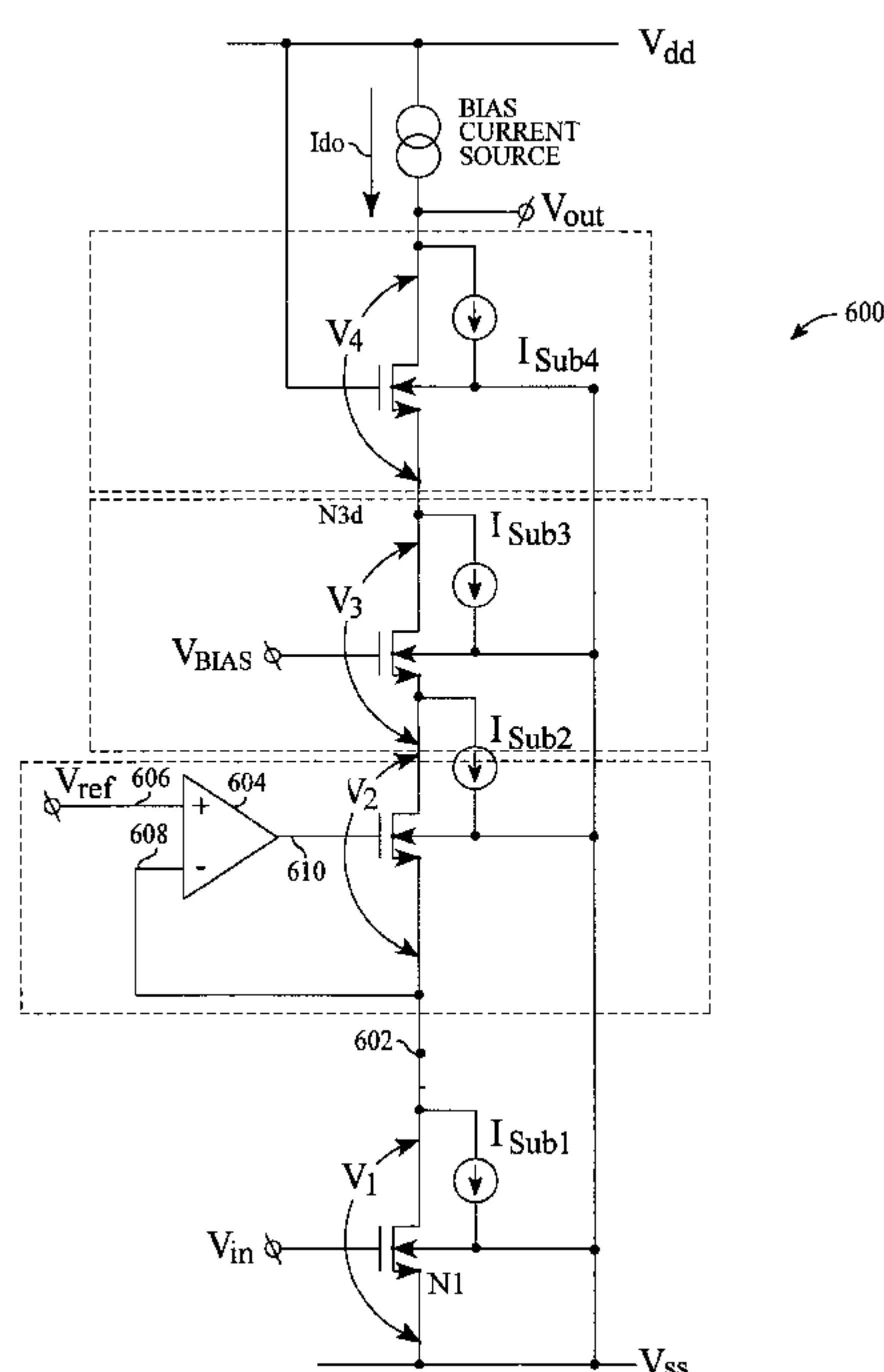
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(57) **ABSTRACT**

MOS Cascode amplifier circuits are subject to long-term or instantaneous changes (degradation) of performance char-

acteristics by excess substrate currents. These currents can be generated in the grounded source transistor of the cascode connected output transistors during peak excursions of drain-source voltage across the grounded source transistor when the output voltage of the MOS Cascode amplifier circuit is at a maximum. An improved MOS Cascode amplifier circuit arrangement includes a voltage limiting bias circuit arrangement of additional transistors. The bias circuit arrangement acts as a series voltage-limiting device between the MOS Cascode amplifier circuit output node and the drain node of the upper-most cascode connected transistors when the MOS Cascode amplifier circuit output voltage is at its maximum value. An embodiment of the improved MOS Cascode amplifier circuit arrangement is arranged to limit the drain-source voltage excursion peak on the sensitive cascode transistor to a value below a pre-selected critical voltage, V_{crit} . V_{crit} is defined as the drain-source voltage value for the sensitive cascode transistor for which the instantaneous and/or cumulative substrate current caused by peak drain-source voltage excursions greater than V_{crit} would instantaneously or cumulatively degrade the transistor's sensitive electrical parameters to an extent that would degrade (an) amplifier performance characteristic(s) to an appreciable degree. The additional transistors of one embodiment of the bias circuit arrangement are connected by internal adjacent source-drain nodes as a sequential chain with gates biased at respective fixed voltages. One external drain node of the chain connects to the output node of the MOS cascode amplifier and one external source node of the chain connects to drain of the uppermost cascode connected transistors. The number of additional transistors and the fixed bias gate voltages are selected to limit the peak drain-source voltage excursion on the sensitive transistor under selected operating conditions.

14 Claims, 7 Drawing Sheets



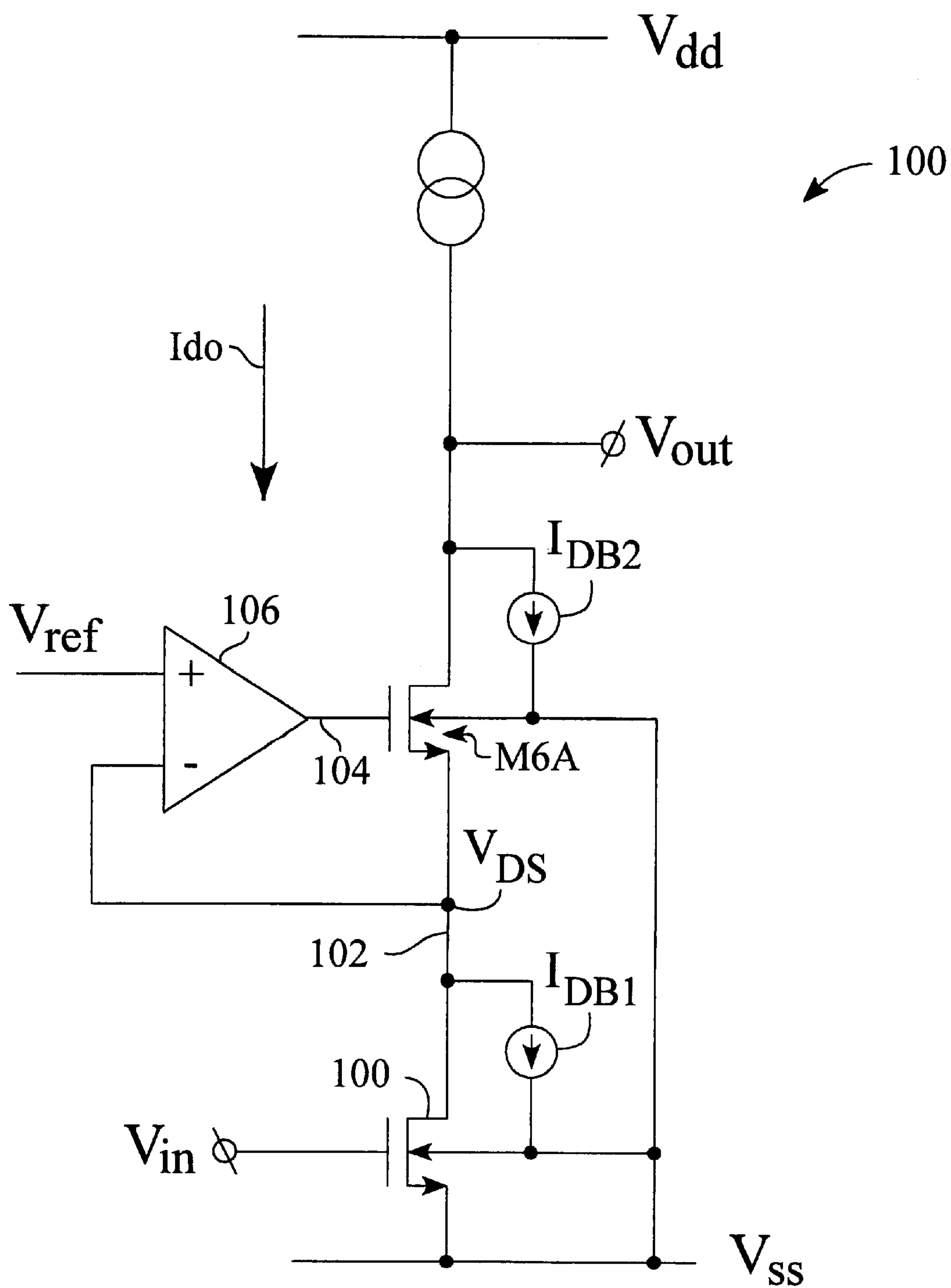
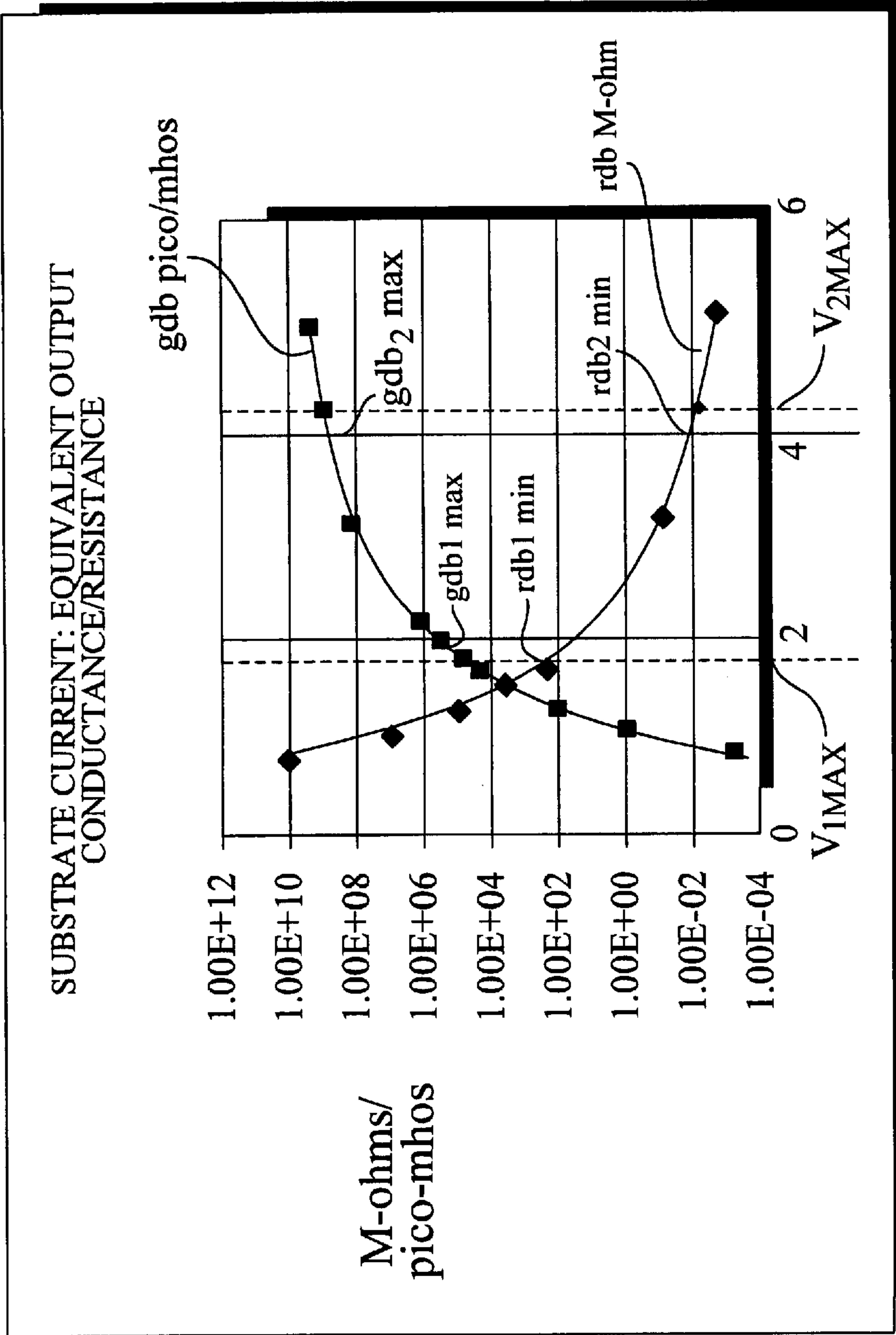


Fig. 1 (Prior Art)



VDS-VDSsat

Fig. 2

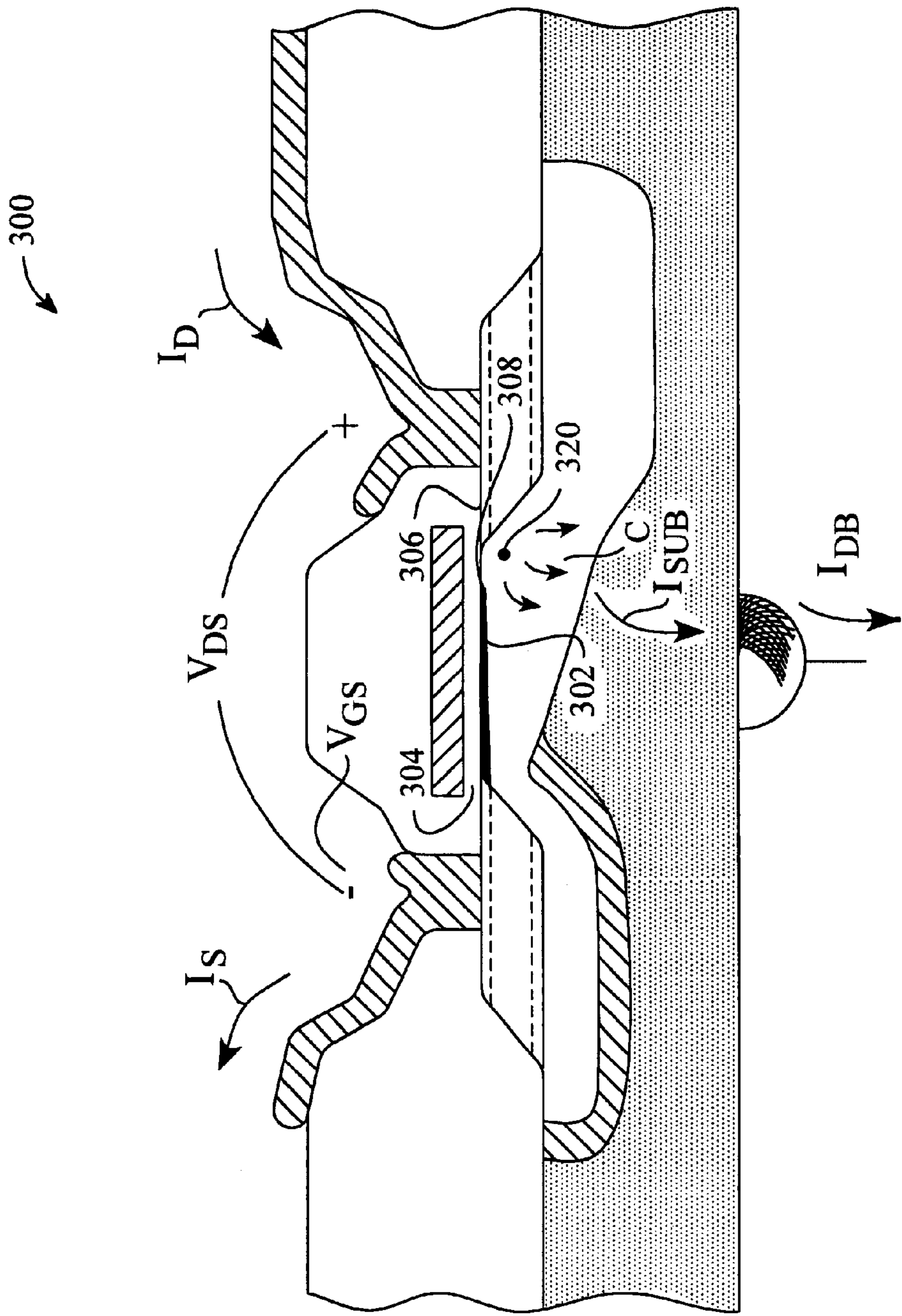


Fig. 3

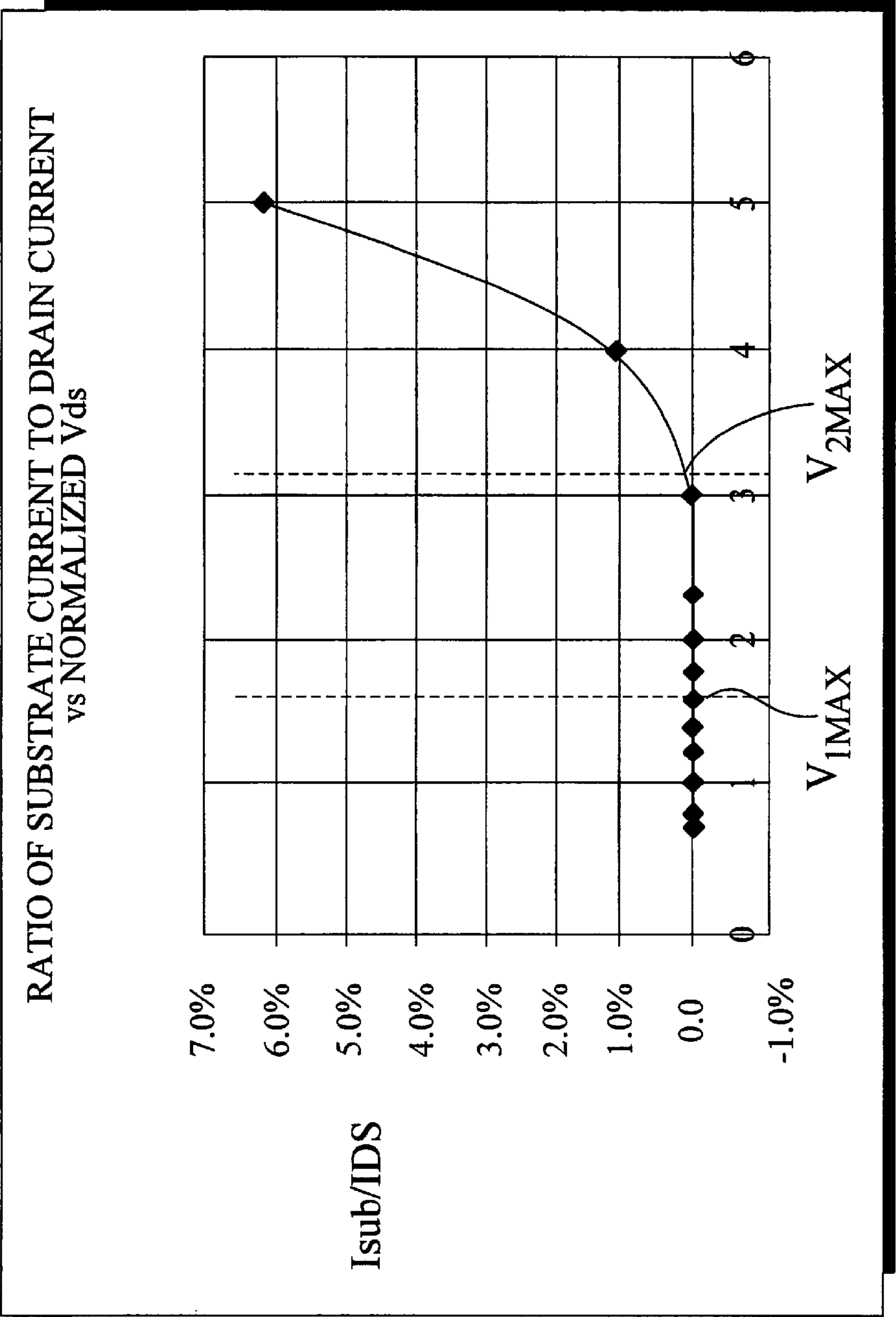


Fig. 4

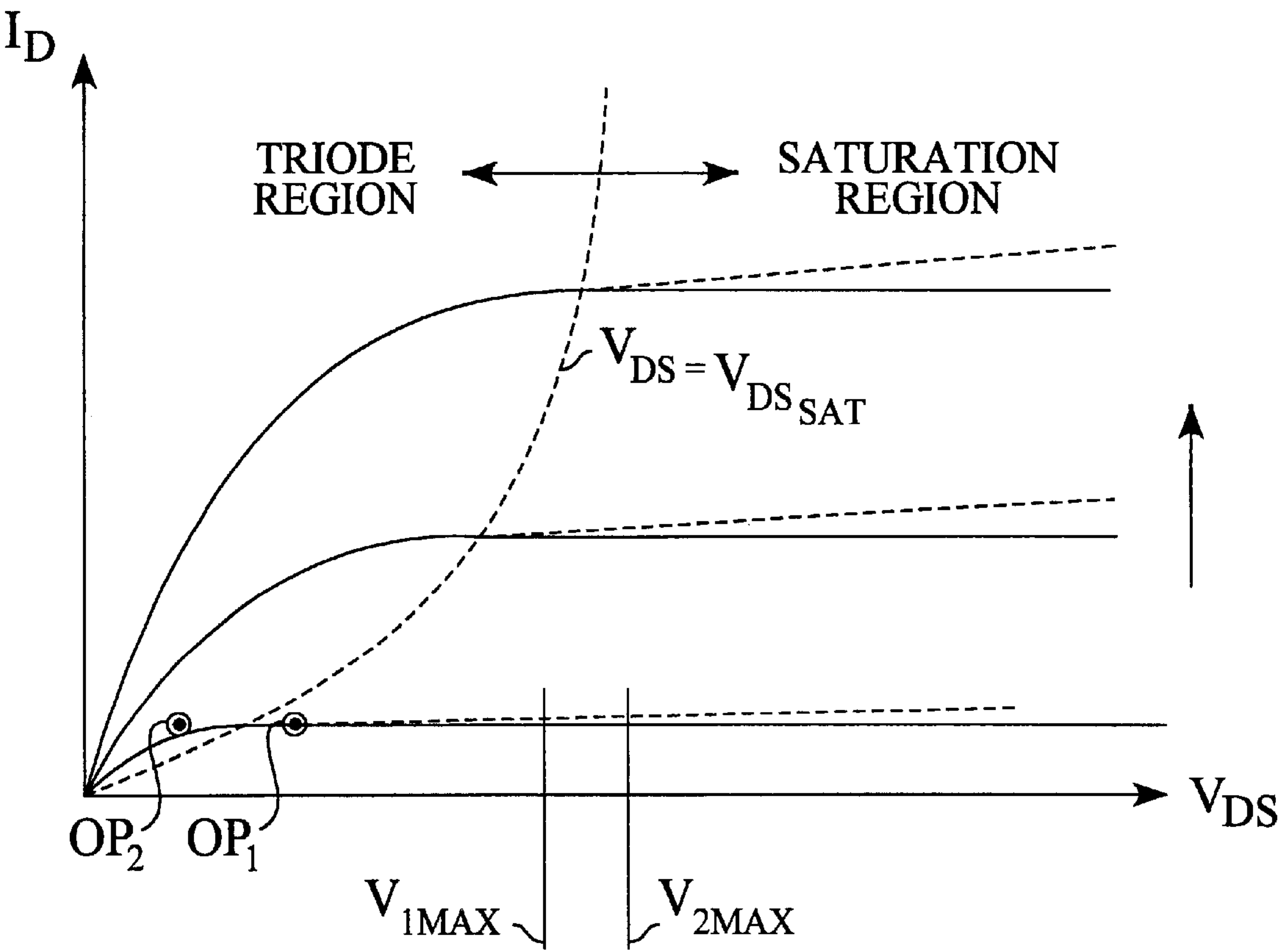


Fig. 5

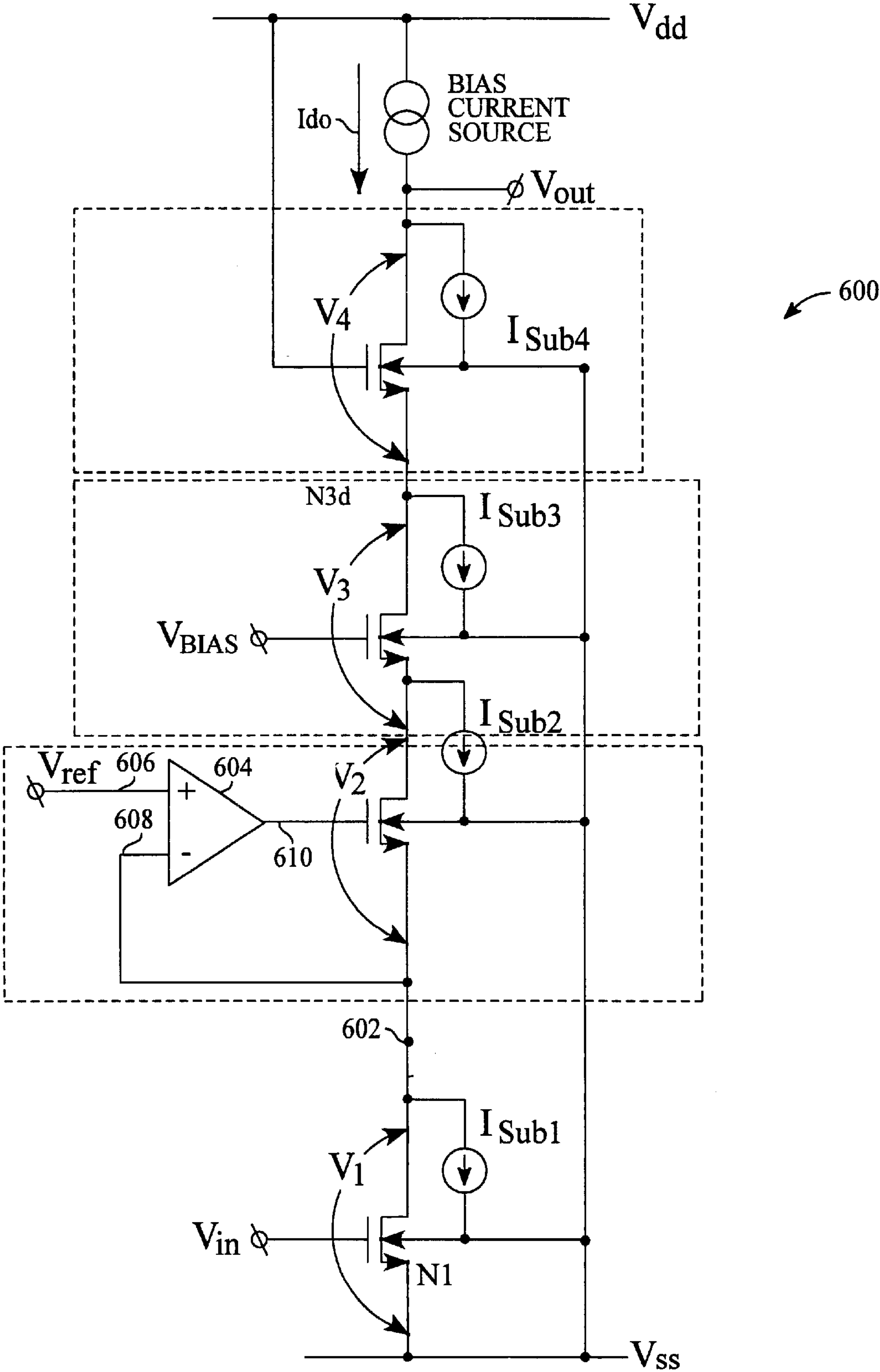


Fig. 6

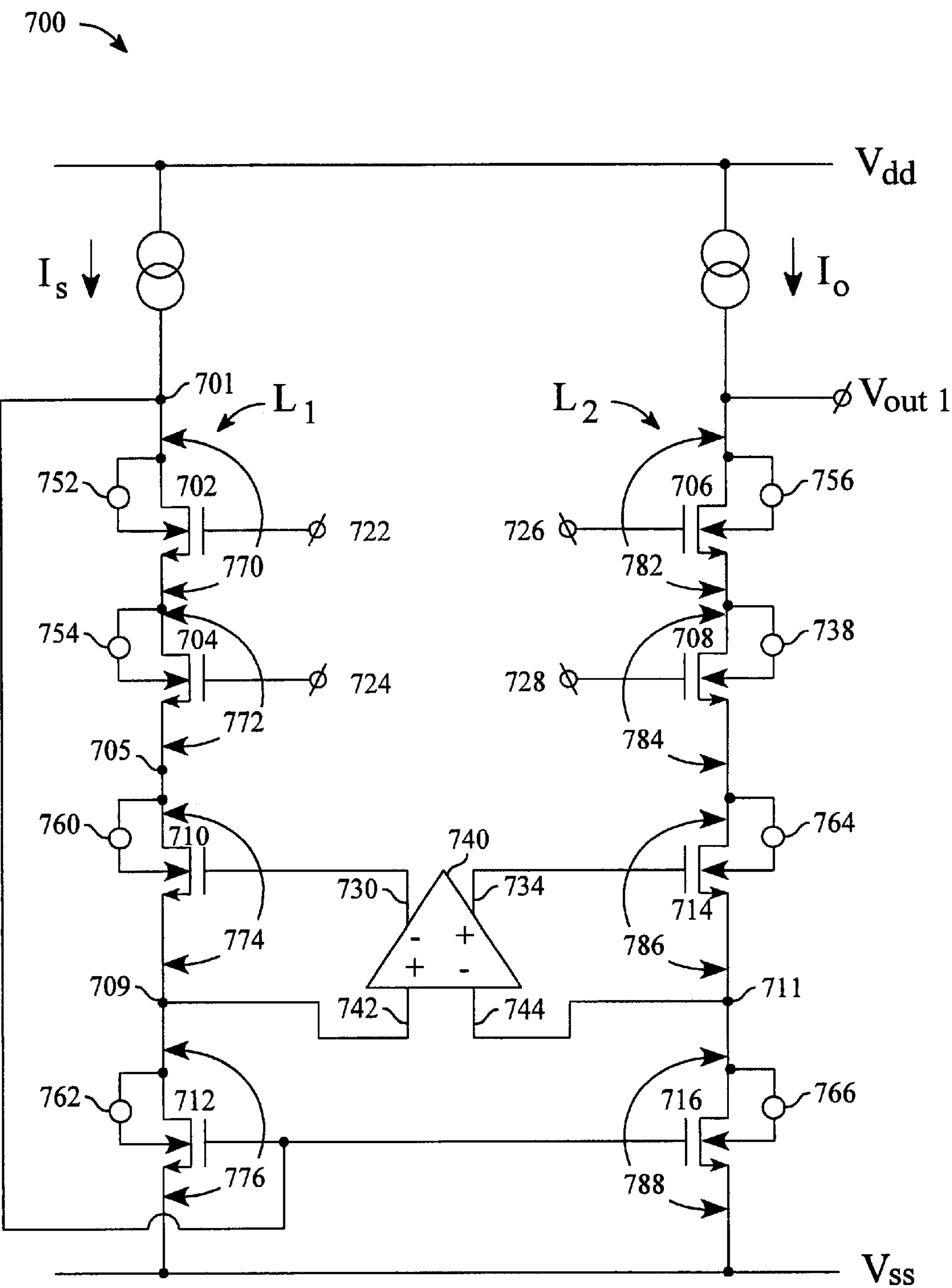


Fig. 7

VOLTAGE LIMITING BIAS CIRCUIT FOR REDUCTION OF HOT ELECTRON DEGRADATION EFFECTS IN MOS CASCODE CIRCUITS

FIELD OF THE INVENTION

This invention relates generally to stabilizing the operational performance of MOS circuits and specifically to minimizing limitations on cascode amplifier circuit performance and reliability caused by excessive substrate current induced by hot electrons from high drain-to-source voltages.

BACKGROUND

In MOS amplifier and current mirror circuits, transistors biased into the saturation to region can experience an undesirable substrate current arising from impact ionization (due to the so-called "hot electron" effect). Impact ionization in the MOSFET channel is described in the literature and is generally known by circuit design practitioners.

A physical model of this effect is depicted in a single p-well n-channel transistor **300** of FIG. **3**. Transistor **300** is shown biased in saturation, that is, with the inversion layer **302** under the gate oxide **304** terminating short of the edge of the actual drain diffusion **306** at a pinch-off point **308**. This pinch-off point **308** occurs at a drain-to-source voltage (V_{ds}) of V_{dssat} . The drain current I_D increases relatively little as drain-to-source voltage V_{ds} increases beyond V_{dssat} . The location of the pinch-off point **308** is shown as offset from actual edge of the diffusion **306**, which is the case when V_{ds} is greater than V_{dssat} .

At constant gate-to-source voltage V_{gs} , the pinch-off point **308** moves relatively little as V_{ds} increases. Consequently, the drain current I_D changes relatively little as well. This is shown in the V-I characteristics of FIG. **5**, where the I_D vs. V_{ds} operating characteristic shows the transistor operating in one of two regions, the triode region with low drain-source impedance, and the saturation region with high drain-source impedance.

Beyond V_{dssat} , the transistor region between the inversion layer end **308** and the edge of the drain **306** sustains nearly all of the increased voltage potential between drain and source. At sufficiently high V_{ds} , the electric field in the depletion region between inversion layer **302** and the edge of drain **306** can cause electrons flowing from the end of the inversion layer **308** to the drain **306** (i.e., in the depletion region) to gain additional energy. With sufficient additional energy, the free carriers in the depletion region cause impact ionization, and generate additional free carriers (electron-hole pairs **320**).

These additional free carriers **320** are swept out of the depletion region by the high electric field. Some of the resulting free holes flow into the P-type substrate region as majority carriers, creating a substrate current I_{sub} that increases with V_{ds} , as illustrated in FIG. **4**. Some of the free electrons are swept into the N-type drain region as majority carriers and add to the drain current I_{ds} . These two charge carrier flows appear as an additional component I_{sub} of the total current in the drain and substrate terminals.

An empirical expression for the impact ionization substrate current I_{sub} is given by,

$$I_{sub}=K1 (V_{ds} B V_{dssat})^n Id*(exp [-[K2/(V_{ds}-V_{dssat})]]),$$

Where $K1$ and $K2$ are process-dependent parameters and V_{dssat} is the value of V_{ds} where the drain characteristics enter the saturation region. Under normal operating

conditions, MOS devices have essentially zero substrate current. Oust the leakage current of the reverse biased drain-to-substrate depletion region), as illustrated in FIG. **4**. The effect is generally much less significant in PMOS devices because the lower mobility holes in the depletion region are less efficient in creating hole-electron pairs than are the higher mobility electrons.

Differentiating this expression with respect to drain voltage, the small signal shunt conductance (g_{db}) from drain to substrate is given as,

$$g_{db}=K2 [I_{SUB}]/(V_{ds}-V_{dssat})^n, 2.$$

Substituting for I_{SUB} with the previous expression and rearranging factors produces:

$$g_{db}=K2K1(V_{ds}-V_{dssat})^{-1}(exp[-[K2/(V_{ds}-V_{dssat})]]).$$

FIG. **2** illustrates a plot of g_{db} and its inverse, r_{db} , for a typical NMOS transistor. r_{db} is the equivalent substrate current drain-to-body output resistor that would combine in parallel with the normal transistor output resistance r_o . r_{db} is calculated for a typical NMOS transistor with $K1=5 \text{ V}^{-1}$ and $K2=30 \text{ V}$ and plotted vs. normalized drain-source voltage, $V_{ds}-V_{dssat}$. Also plotted is the equivalent output conductance, g_{db} , which is the inverse of r_{db} . The extreme nonlinear behavior of I_{sub} causes the parallel combination of r_{db} and r_o to be essentially r_o at drain voltages around V_{dssat} and below, since r_{db} is many orders of magnitude greater than typical r_o .

However, at instantaneous drain-to-source voltages not much higher than a few times V_{dssat} , the output impedance of the transistor can be completely dominated by r_{db} . This is one example of how instantaneous or cumulative changes in hot-electron induced substrate current can influence the magnitude and/or variability of device characteristics. This influence can limit and sometimes defeat the possibility of achieving or maintaining desired performance circuit functionality.

As the instantaneous drain-to-source voltage of the transistor varies during operation, the instantaneous amount of the substrate current also varies causing variation of the small signal output conductance. Depending on the operating point and the output voltage swing of the cascode circuit (between the maximum required output voltage and the minimum possible output voltage), the substrate current I_{sub} can vary dramatically. I_{sub} can vary from a value essentially equal to zero at low and moderate V_{ds} to a value that represents a significant portion of the total drain current as the instantaneous V_{ds} approaches the maximum required output voltage or exceeds a critical value. The critical value of V_{ds} ($V_{ds}=V_{crit}$) for the onset of significant I_{sub} (i.e., $V_{ds}=V_{crit}$) depends on the available power supply voltage, the particular circuit function and performance factor(s) at issue, the transistor technology, the transistor dimensions (primarily channel length), and the bias and signal levels. Highly nonlinear circuit behavior may occur depending on the level of the output voltage. If the substrate current magnitude or the magnitude of current variation is substantial compared to the expected drain current or normal drain current variation, it may adversely effect circuit functional performance, behavior and reliability.

This critical value V_{crit} depends on the details of the transistor construction, the magnitude of the instantaneous differences between drain, gate, source and substrate voltages and the drain current. The magnitude of the substrate current is a highly nonlinear function of the voltage differences and current, and can vary by orders of magnitude over

very small changes in the instantaneous terminal voltages. The substrate current is affected most by the drain-to-source voltage V_{ds} once V_{ds} approaches V_{crit} for the particular transistor technology, geometry and circuit voltage conditions.

The performance of a circuit may be affected by this radically nonlinear I_{sub} behavior primarily in two ways. First, radical variation of I_{SUB} may limit one or more selected characteristics of circuit performance (bias current, switching voltage threshold, switching time delay, gain, distortion, noise, and the like). A momentary increase in I_{SUB} at a high V_{ds} voltage above critical value V_{crit} causes an unacceptable momentary change in an electrical device parameter from its nominal design value. Second, cumulative changes or drifts in a device electrical parameter e.g., parameters such as threshold voltage, transconductance, leakage current and the like may affect circuit performance. Sufficient shifts in device parameters may cause a consequent reduction of the Mean-Time-to-Failure (MTBF) for circuits of a given type, i.e. decreased reliability.

A circuit having a device with one or more electrical parameters that change rapidly with small changes of signal voltage, or output voltage level, essentially independent of the gate-source control voltage may also exhibit unacceptable changes in circuit performance, e.g., non-linear gain, distortion, impedance mismatch, and the like.

The long-term effects of excess substrate current are exhibited by slow degradation of the device electrical parameters (V_{th} , G_m , sub-threshold leakage, etc.). The hot carriers that cause I_{sub} are known to cause charge trapping in the gate oxide, which, over time, causes threshold, transconductance and sub-threshold behavior shifts. Eventually, the degradation of the device parameters due to excess substrate current will reach a level where the cascode circuit performance will no longer meet the required specification and the cascode circuit will fail.

Deterioration of transistor characteristics by substrate current is known to cause undesirable changes in performance of circuits over time. The literature describes transistor modeling and circuit simulation techniques for calculating the influence of I_{sub} on circuit behavior. Known I_{sub} vs. V_{ds} models (e.g., the modified Mar's model and Sakurai's model described elsewhere) and simulators (the known RELY simulator described elsewhere) are combined with a segmented or iterative simulation scheme.

Referring to FIG. 1 a prior art attempt to reduce degradation of performance characteristics of a simple amplifier output circuit due to substrate current and thus to improve the circuit behavior is shown. An amplifier circuit stage consisting of a simple grounded source single transistor output stage is replaced by a circuit arrangement **100** of a two transistor series combination: transistor **M6A**, and **M6**. This series combination is generally referred to as a cascode connection with **M6A** being the upper cascode transistor **M6a** and transistor **M6** being the grounded source lower transistor. Upper cascode transistor **M6A** is interposed between the drain of the grounded source transistor and the amplifier output with its output drain node connected to amplifier output V_{out} and its source node connected to the drain of the grounded source transistor **M6**.

M6 is driven by input V_{in} and **M6A** has its gate connected to a reference voltage V_{ref} . The arrangement of transistor **M6** in series between output amplifier node V_{out} and the **M6** drain node partially ameliorates degradation of the circuit gain $G_c = \Delta V_{out} / \Delta V_{in}$, (a selected circuit functional characteristic) and defers catastrophic failure of this functional characteristic for this particular analog circuit under a par-

ticular voltage stress. Including the V_{ref} biased common-gate buffering transistor **M6A** between the drain **102** of the grounded-source output transistor **M6** and the voltage output terminal V_{out} converts the output stage **100** into a cascode output and reduces the maximum V_{ds} voltage stress on transistor **M6** during peak output voltage excursions.

The peak substrate current I_{sub1} in transistor **M6** before the substitution is made is about 10 ma during the peak voltage excursion (4 volts) at the output, V_{out} . After the substitution of the grounded-gate cascode transistor, **M6A**, the gate **104** of **M6A** is biased by V_{ref} , a fixed voltage reference. V_{ref} is chosen to set the gate of **M6A** so that the maximum V_{ds} across transistor **M6** is limited (and thus limiting the peak I_{sub} in transistor **M6**) during the peak excursion of V_{out} .

Transistor **M6A** is biased so that, as the drain-source voltage V_{ds} for transistor **M6** approaches V_{ref} minus the threshold voltage V_t of **M6A**, transistor **M6A** begins to turn off (move from the triode region to the saturation region) and absorb additional voltage supplied by source current I_{do} from the power supply V_{dd} . V_{ds} thus will be limited to a maximum value of about V_{ref} minus V_t . V_{ref} and **M6A** limits V_{ds} across transistor **M6** to V_{dsmax} such that with V_{dd} of 10 volts and V_{out} at the desired 4 volts, the peak value of transistor **M6** substrate current (I_{sub1}) is reduced to essentially zero. The cascode connection causes the 4-volt peak to be shared by transistor **M6** and **M6A**.

With I_{sub1} reduced to essentially zero, the gain, G_c , of the circuit is therefore stabilized so that after 115 days of simulated operation, instead of 40% degradation, there is essentially a negligible shift in gain. This provides some reduction in performance degradation sought by the inclusion of the grounded-gate transistor **M6A** biased to limit the peak V_{ds} across transistor **M6**.

However, the cascode transistor **M6A** now takes up part of the voltage stress previously fully absorbed by transistor **M6**. Although I_{sub} for **M6A** is lower than the previous value for transistor **M6** (4 ma vs. 10 ma), it is still considerable. Since the operating point of **M6A** is biased closer to or into the triode region for low values of V_{ds} , its impedance is lower than transistor **M6** and consequently it has much less effect on the gain of the circuit **100**. However, with the still relatively high value of I_{sub} in **M6A**, the prospect of a stable circuit gain over a long life is not assured.

Regulated cascode circuits described in the literature can produce even higher gain than ordinary cascode circuits. See U.S. Pat. 5,039,954 by Bult et al., and U.S. Pat. No. 5,748,040 by Leung, incorporated herein by reference. Their utilization is somewhat restricted to small voltage swings and low to moderate output voltage levels because this high gain is achieved only at low drain-to-source voltage. Because their higher gain is achieved by high output impedance they are even more susceptible to hot electron induced substrate current. At higher output voltage, i.e., high V_{ds} , the gain is reduced to levels similar to ordinary cascode circuits.

Additionally, the local feedback used in previous regulated cascode circuits generally monitor source current to maintain circuit function. However, the excess substrate current from hot-electron effects does not flow in the source loop, so is not subject to the benefits of the regulated cascode local feedback.

These and many other examples of substrate current (hot electron effects) causing limited and/or degraded circuit performance for critical circuit functional characteristics and consequent decreased reliability are known in the integrated circuit arts. Performance and reliability limitations imposed on using known circuits to provide useful circuit functions

are increasing as the trend for lower device operating voltages continues over time. The ever-increasing demand for faster circuit performance impels the continuing decrease in active electrical circuit dimensions and consequent increased sensitivity to degradation by substrate current.

There is a large and pressing need to provide improvements in circuits to obviate these limitations on circuit designers and manufacturers.

SUMMARY

MOS Cascode amplifier circuits are subject to long-term or instantaneous changes (degradation) of performance characteristics by excess substrate currents. These currents can be generated in the grounded source transistor of the cascode connected output transistors during peak excursions of drain-source voltage across the grounded source transistor when the output voltage of the MOS Cascode amplifier circuit is at a maximum. The improved Cascode amplifier circuit arrangement of the present invention includes a voltage limiting bias circuit arrangement of additional transistors. The bias circuit arrangement acts as a series voltage-limiting device between the MOS Cascode amplifier circuit output node and the drain node of the upper-most cascode connected transistors when the MOS Cascode amplifier circuit output voltage is at its maximum value. An embodiment of the improved MOS Cascode amplifier circuit arrangement is arranged to limit the drain-source voltage excursion peak on the sensitive cascode transistor to a value below a pre-selected critical voltage, V_{crit} . V_{crit} is defined as the drain-source voltage value for the sensitive cascode transistor for which the instantaneous and/or cumulative substrate current caused by peak drain-source voltage excursions greater than V_{crit} would instantaneously or cumulatively degrade the transistor's sensitive electrical parameters to an extent that would degrade (an) amplifier performance characteristic(s) to an appreciable degree.

The additional transistors of one embodiment of the bias circuit arrangement are connected by internal adjacent source-drain nodes as a sequential chain with gates biased at respective fixed voltages. One external drain node of the chain connects to the output node of the MOS cascode amplifier and one external source node of the chain connects to drain of the uppermost cascode connected transistors. The number of additional transistors and the fixed bias gate voltages are selected to limit the peak drain-source voltage excursion on the sensitive transistor under selected operating conditions.

Embodiments of the voltage-limiting, substrate current minimizing, bias circuit arrangement of the present circuit invention can significantly extend circuit performance, operational lifetime or significantly reduce unwanted circuit performance limitations or decreased reliability resulting from momentary or cumulative electrical parameter variation effects caused by excessive substrate current in individual transistors of over stressed amplifying stages.

The prior art approach of the fixed-gate-biased transistor (effectively grounded gate for small-signal equivalence) interposed between the grounded-source drain and the output terminal disclosed by Hsu, et al., does reduce the substrate current in the transistor M6 enough to extend the lifetime of the circuit described somewhat. However, transistor M6A itself now may experience a considerable amount of substrate current at peak voltages that eventually may degrade its threshold voltage or shunt conductance sufficiently to unacceptably alter the circuit performance.

Embodiments of the present Cascode circuit bias circuit arrangement invention incorporate a first transistor chain,

having at least one additional transistor, connected in series between a Cascode circuit output voltage terminal and the drain of a first transistor in a second cascode transistor series chain where the second cascode transistor chain is connected at its source end to circuit ground). The additional transistor(s) in the first chain is (are) biased by fixed voltages at respective gate terminal(s) to limit respective maximum drain-to-source voltages across two or more individual transistors in the second cascode transistor chain. The maximum drain-to-source voltages are limited to respective maximum values below respective critical voltage levels (V_{crit}) at which respective substrate currents in the corresponding two or more individual transistors unacceptably change a circuit performance characteristic, (e.g. gain, output impedance, operational lifetime and the like). Additionally, embodiments of the present invention improve reliability, by postponing the circuit's end-of-life, i.e., lengthening the time over which selected circuit characteristics meet predetermined levels.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a prior art cascode output circuit;

FIG. 2 exhibits a graph of typical small-signal equivalent output resistance variation due to substrate current;

FIG. 3 depicts a cross-sectional view of an NMOS transistor illustrating the origin and terminal path for substrate current;

FIG. 4 exemplifies typical normalized substrate current I_s vs normalized drain-to-source voltage showing the rapid increase at a critical V_{ds} level;

FIG. 5 shows a typical N-channel MOS device characteristic and corresponding operating regions;

FIG. 6 illustrates one embodiment of a transistor drain-source voltage-limiting bias circuit arrangement for a cascode output circuit according to the present invention; and

FIG. 7 displays an alternative embodiment of the drain-source voltage-limiting bias circuit arrangement for a cascode current mirror circuit according to the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE PRESENT INVENTION

Two basic assumptions are central to determining stability of circuit performance (e.g. a requirement set $\{R\}$) from variations caused by excess substrate currents. The first factor is the determination or specification of which circuit functional characteristic (gain, output resistance and the like) is to be stabilized. The second factor is the determination of how much variation or degradation of selected circuit performance characteristic(s) is allowable over what MTBF. Means for relating these factors to embodiments of the present invention is outlined below.

Circuit analysis techniques, simulation methods and physical electronics characteristic effects are known in the art and are shown in the references cited herein and in other references commonly known by one skilled in the electronic arts. Use of these techniques, methods, and knowledge is within the capability of a person having ordinary skill in the pertinent technical arts of physical electronics and electrical circuit theory and practice.

With regard to FIG. 6 one embodiment of the present performance stabilizing invention is depicted as an n-well CMOS cascode output amplifier stage 600. Transistors N1 and N2 are connected as a cascode pair, with N1 source connected to a common circuit ground terminal V_{ss} . An

input source signal V_{in} drives N1's gate, and transistors N2 and N1 are joined by respective source and drain terminals at a common drain-source connection 602. V_{in} has upper and lower limits V_{in-u} , V_{in-l} established by a selected requirement set $\{R\}$ of particular operating requirements for the circuit 600.

Additional transistors N4 and transistor N3 are connected in serial source-drain sequence with N4's source coupled to N3's drain. N3's source is similarly coupled to N2's drain. N4 has its drain coupled to output terminal Vout. Output terminal Vout receives a source of current I_{do} provided from power-supply terminal Vdd. N3's gate receives a fixed bias voltage V_{bias} from a fixed bias supply terminal. N4's gate is also biased at a fixed voltage by being coupled to power-supply terminal Vdd.

The embodiment 600 of the present invention includes an amplifier, e.g., differential amplifier 604 having a positive sense (non-inverting) input 606 and negative sense (inverting) input 608. An output terminal 610 provides a positive going output voltage responsive to the potential difference between non-inverting terminal 606 and inverting terminal 608. The output terminal 610 is connected to N2's gate. Non-inverting input 606 receives a fixed voltage reference V_{ref} . Inverting input 608 connects to the common drain-source connection 602 of N2 and N1.

Amplifier 604 is selected with suitable additional amplifier characteristics (e.g. input impedance, output impedance, gain, bandwidth and the like) appropriate to cooperate with the cascode transistors N1, N2 and the additional transistors N3, N4 to meet the requirement set $\{R\}$. Amplifier 604 and transistors N1, N2, N3, and N4 thus co-operate with the bias voltages V_{ref} and V_{bias} to stabilize the performance requirement set $\{R\}$ against unacceptable variation in performance caused by substrate currents.

V_{ref} is selected so that Amplifier 604 biases the transistor M6A to maintain transistor M6 in its saturation region under selected operating conditions of the circuit 600 as outlined below.

A particular set of operating requirements $\{R\}$ established for the circuit 600 generally includes a requirement that the power-supply Vdd can assume voltage values up to a maximum value V_{ddmax} . The set of operating requirements, $\{R\}$, may also include other functional and/or operational circuit requirements R1, R2, - - - R(m), e.g., a minimum gain requirement $G_{min} > R1$, a maximum output voltage value, $V_{out\ max} < R2$, a maximum input signal voltage level $|V_{in}| < R3$, an operating mean-time-to-failure $MTBF > R4$, a minimum output voltage swing $V_{out} > R5$, among others.

For embodiments of the performance stabilizing bias circuit of the present invention, requirement set $\{R\}$ also includes the constraint that the respective drain-to-source voltages V1, V2 across cascode transistors N1 and N2 will not exceed respective maximum safe values $V1\ max$ and $V2\ max$.

Alternatively, additional constraints may be placed on additional transistors N3, and N4 that the respective drain-to-source voltages V3, V4 across additional transistors N3 and N4 will not exceed respective maximum safe values $V3\ max$ and $V4\ max$.

To summarize, V_{bias} and V_{ref} are selected so those transistors N1-N4 and amplifier 604 co-operate to meet the following constraint conditions:

1. If the output voltage Vout is low (i.e., near V_{ss}), N2, N3 and N4 are biased in their respective triode regions (i.e. operating point OP2 of FIG. 5), so they do not significantly contribute to circuit gain ($\Delta V_{out}/\Delta V_{in}$).

2. Also, when output voltage Vout is low (e.g., at some $V_{out-min}$, near V_{ss}), transistor N1 is biased so that it is in its saturation region (i.e. operating point OP1 of FIG. 5) so that its output impedance is high and the circuit 600 meets the gain requirement of the set $\{R\}$.

3. In addition, V_{ref} and V_{bias} are also selected so that when the output voltage Vout is high (i.e., near V_{dd}), respective drain-to-source voltages V1, V2 across the respective drain-to-source terminals of transistors N1, N2, (and V3, V4 across N3, N4, if so constrained) do not exceed respective maximum safe levels $V1\ max$, $V2\ max$ (and $V3\ max$, $V4\ max$) under the requirement set $\{R\}$.

4. The respective safe levels (extrema) $V1\ max$, $V2\ max$, $V3\ max$, $V4\ max$ are selected to keep substrate currents I_{sub1} , I_{sub2} , I_{sub3} , I_{sub4} to less than respective maximum levels I_{sub1m} , I_{sub2m} , I_{sub3m} , I_{sub4m} .

The respective safe levels $V1\ max$, $V2\ max$, $V3\ max$, $V4\ max$ for respective drain-source terminal (nodes pairs) of circuit 600 constitute a set of extreme voltage values $\{V_i\}$ part of a set of constraints $\{S_j\}$ that include the requirement set $\{R\}$. The constraints $\{S\}$ include, for example, the gain G_c the maximum supply voltage V_{ddmax} , the maximum and minimum input signal voltages, V_{in-max} , V_{in-min} , and others. The set of extreme voltages $\{V_i\}$ are selected based on a corresponding set of maximum safe substrate currents, I_{sub1m} , I_{sub2m} , I_{sub3m} , and I_{sub4m} ($\{I_{sub}\}$).

The maximum substrate current levels I_{sub1m} , I_{sub2m} , I_{sub3m} , and I_{sub4m} are established by the particular technology and requirement set $\{R\}$ chosen for the circuit 600, e.g., for instantaneous gain stability and long-term reliability (i.e. low levels of parameter degradation).

The selection of the respective maximum substrate current levels I_{sub1m} , I_{sub2m} , I_{sub3m} , I_{sub4m} to be allowed for the particular embodiment 600 of the present invention can be achieved by simulation of the circuit 600 using known integrated circuit models and known circuit synthesis and analysis tools. Known models and tools for calculating transistor and circuit behavior with regard to the transistor output resistance (conductance) variation with substrate current are shown by W. Hsu et al. "Design of Reliable VLSI Circuits Using Simulation Techniques", IEEE Journal of Solid-State Circuits, Vol. 26, pp. 452-457, March 1991, incorporated herein by reference.

The computation of the set of voltage extrema $\{V_i\}$ for the circuit 600 under constraints $\{R\}$ can be obtained by ordinary practitioners in the arts of circuit design, analysis and synthesis familiar with standard methods. Methods and techniques for circuit analysis and synthesis are shown in standard college texts such as "Principles of Circuit Synthesis", E. S. Kuh, and D. O. Pederson, McGraw-Hill, New York, N.Y., 1959; and "Analysis of Linear Systems", D. K. Cheng, Addison-Wesley Publishing, Reading, Mass., 1959.

In brief, transistors N1-N4 and amplifier 604 are represented in standard pi or tee equivalent circuit models with a respective set of circuit branches of passive elements $\{P\}$ and active, dependent signal generating elements $\{G\}$. The $\{P\}$ and $\{G\}$ elements are interconnected and result in forming a set of polynomial mesh or current loop equations $\{M\}$ or respective voltage node equations $\{N\}$ that include V_{ss} , V_{dd} , $V1-V4$ and V_{in} and Vout. The passive elements $\{P\}$ and active elements $\{G\}$ are functionally expressed in terms of standard transistor and amplifier model parameters (e.g., $\pi\{W_e, L_e, A_e\}$, $tee\{W_e, L_e, A_e\}$).

The mesh $\{M\}$ or node $\{N\}$ equations are solved by standard linear means to give a set of respective expressions

{Vi} for the drain-source voltages V1–V4. The {Vi} are expressed in the form $w=f(x, y, u, v)$ where w represents one of voltages V1–V4 having an extreme value Vmax, and the variables x, y, u, v represent the constrained bias variables Vref, Vbias and other circuit requirements (e.g., Vddmax, Vin-min) or circuit operational characteristics (e.g. Gc) of the circuit 600.

In general, the n constrained variables x, y, u, v are constrained by m additional relations of the form $N_m(x, y, u, v)=0$. N_m represent constraining equations found from the mesh equations {M} or node equations {N} of the circuit 600.

The standard mathematical technique of LaGrange Multipliers may be used to find the values of Vbias and Vref in terms of the extrema for the drain-source voltage set {Vi} under the several conditions of constraint {S}. This is shown, for example, in “Mathematics of Physics and Engineering”, I. S. Sokolnikoff, and R. M. Redheffer, McGraw-Hill New York, N.Y., 1958, pg. 254–257.

Dimensions of effective electrical length, Le, and width, We, for the individual transistors N1–N4 of the circuit structure of FIG. 6 are selected to achieve selected required gain Gc and impedance values (i.e., output impedance Rout) defined by the requirement set {R}. Methods for selection are made by means familiar to practitioners of integrated circuit design. The dimensions Le, We, as functions of voltages Vdd-max, Vin-u, Vin-l, and the constrained Vbias, Vref required may be determined by combining the requirements of set {R} with circuit simulation and knowledge of the transistor electrical characteristic variation with substrate current. These are all described in the references cited above and are well known in the art by knowledgeable circuit design practitioners.

By proper selection of the bias voltages Vref and Vbias with respect to specified circuit operating conditions, e.g., Vdd, maximum output voltage Voutmax, Vinu, and Vinl, the maximum required output voltage Vout-max is spread over more than one transistor. This selection reduces the maximum Vds voltage across each transistor N1–N4 from the full value of Vout-max, to no more than the respective desired maximum safe level, i.e., V1-max, V2-max, V3-max, V4-max.

Alternatively the bias levels Vref, Vbias may be selected so that in addition to the limitations of the safe voltage levels, transistor N1 may operate slightly above or into saturation to maximize gain Gc and output voltage swing (e.g., Vout).

In still another alternative for the present invention Vref, Vbias may be selected so that in addition to the limitations of the safe voltage levels, the circuit performance also achieves a maximum output voltage Voutmax at a gain, Gc, slightly reduced from a maximum achievable gain.

The distribution of maximum voltages on transistors N3 and N4 is maintained by biasing their gates to substantially fixed potentials either by connecting directly to power supply potentials, or indirectly by driving from low impedance op-amps referenced to fixed potentials obtained from, e.g., a power supply connected to a multi-tap voltage divider, for example a resistive divider.

The method described above for selecting the bias voltages, Vref, and Vbias to enable performance of the circuit 600 to be stabilized against parameter variation caused by excess drain-source voltage extrema across one or more of the transistors N1–N4 is summarized as a series of steps in the outline below.]

METHOD FOR CHOOSING BIAS VOLTAGE VALUES FOR THE CIRCUIT OF FIG. 6 TO STABILIZE CIRCUIT

PERFORMANCE CHARACTERISTICS AGAINST VARIATION CAUSED BY EXCESS SUBSTRATE CURRENT.

STEP 1: SELECT ONE OR MORE CIRCUIT FUNCTIONAL CHARACTERISTIC(S) {Cc}; E.G. CIRCUIT GAIN, Gc, OUTPUT IMPEDANCE, r_o AND MAXIMUM MOMENTARY AND/OR END OF LIFE % VARIATION VALUE(S), {c} AS A FIRST PART OF A REQUIREMENT SET {R}.

STEP 2: SELECT ONE OR MORE EXTERNAL CIRCUIT VOLTAGE LIMITS; I.E., EXTERNAL CIRCUIT CONSTRAINTS SET {Vx}, e.g.: VINmin/max, VDDmin/max, VOUTmin/max, VOUTmax.] AS A SECOND PART OF THE REQUIREMENT SET {R}.

STEP 3: PERFORM INITIAL OPERATING POINT BIAS ANALYSIS TO CHOOSE INITIAL FIXED BIAS GATE VOLTAGE VALUES {Vi}. FOR THE GATES N3, - - - N(i), - - - N(n). SELECT THE INITIAL FIXED GATE VOLTAGE VALUES {Vi} TO OPERATE THE SELECTED TRANSISTORS {Nn} IN RESPECTIVE INITIAL SATURATION AND TRIODE OPERATING POINTS ({OP1 FOR TRANSISTOR N1, OP2n FOR TRANSISTORS N2, N3, CNn). NOTE: FOR ONE ADDITIONAL TRANSISTOR, N3, i=1 AND {Vi}=(Vref),. FOR TWO ADDITIONAL TRANSISTORS, N3, N4, i=2 AND {Vi}=e.g. Vref, Vbias..

STEP 4: PERFORM ELECTRICAL CIRCUIT ANALYSIS AND SYNTHESIS WITH THE SELECTED 600 CIRCUIT TRANSISTORS {Nn}, BIASES {Vi} UNDER THE GIVEN CONSTRAINTS.

NOTE: IF REQUIRED, PERFORM ELECTRICAL CIRCUIT ANALYSIS AND SYNTHESIS TO SELECT TRANSISTOR WIDTHS AND LENGTHS {Wn, Ln} FOR THE SELECTED {Nn} TRANSISTORS N1, N2, N3, - - - Nn, TO MEET THE REQUIREMENT SET {Cc}, (e.g. Gc AND r_o)

STEP 5: PERFORM CIRCUIT ANALYSIS AND SIMULATION ON THE CIRCUIT 600 FROM STEP 3 WITH KNOWN SIMULATION TOOLS AND METHODS TO COMPUTE INITIAL, MOMENTARY AND END-OF-LIFE PERFORMANCE.

5A: COMPUTE WORST CASE MOMENTARY PEAK AND CUMULATIVE (END OF LIFE) EXPECTED SUBSTRATE CURRENTS {Isubn} FOR THE TRANSISTORS {Nn}.

5B: CONFIRM THAT THE SERIES SUM OF TRANSISTOR VOLTAGE EXTREMA FOR THE TRANSISTORS {Nn} EQUALS THE MAXIMUM OUTPUT VOLTAGE: $V_n \max = VOUTmax$.,

5C: COMPUTE WORST CASE MOMENTARY PEAK VOLTAGE EXTREMA {Vn max} FOR THE TRANSISTORS {Nn}

5C: COMPUTE INITIAL, WORST CASE MOMENTARY PEAK AND CUMULATIVE ELECTRICAL PARAMETER VARIATION AND WORST CASE MOMENTARY PEAK AND CUMULATIVE VARIATION(S) OF THE CIRCUIT PERFORMANCE CHARACTERISTIC(S) {C}c.

STEP 7: TEST 1: IS (ARE) THE COMPUTED CIRCUIT PERFORMANCE CHARACTERISTIC VARIATION(S), {c}c, DUE TO SUBSTRATE CURRENT GENERATION WITHIN CONSTRAINED LIMITS {c} ? IF YES, GO TO END, IF NO, GO TO NEXT STEP.

STEP 8: TEST 2: IS THE EXCESSIVE VARIATION OF THE COMPUTED WORST CASE MOMENTARY

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PEAK AND CUMULATIVE CIRCUIT PERFORMANCE CHARACTERISTIC VARIATION(S), DUE TO EXCESS SUBSTRATE CURRENT GENERATION ($I_{sub(i)}$) IN TRANSISTOR (i) CAUSED BY AN EXCESSIVELY LARGE VALUE OF DRAIN-SOURCE VOLTAGE EXTREME $V_{ds(i)max}$, RELATIVE TO THE VALUES OF DRAIN-SOURCE VOLTAGE EXTREMES $\{V_{ds(n-1)max}\}$ OF THE OTHER $n-1$ DRAIN-SOURCE SERIES CONNECTED TRANSISTORS? IN OTHER WORDS, IS THERE AN IMBALANCE IN THE DISTRIBUTION OF DRAIN-SOURCE VOLTAGES $V_{ds(i)max}$ BETWEEN TRANSISTOR N_1 AND TRANSISTORS $N_2, N_3, \dots, N_i, \dots, N_n$ SO THAT THE TOTAL V_{outmax} CAN BE REDISTRIBUTED ACROSS THE TRANSISTORS $\{N_n\}$?

IF TEST 2 IS YES SKIP NEXT STEP, IF NO, DO NEXT STEP.

STEP 9: CHANGE THE CIRCUIT CONFIGURATION OF CIRCUIT 600 TO INCLUDE AN ADDITIONAL DRAIN-SOURCE CONNECTED TRANSISTOR $N(i+1)$ IN SERIES WITH N_3 , (and/or N_4), BETWEEN V_{out} AND THE DRAIN OF N_2 , AND ADD AN ADDITIONAL FIXED BIAS VOLTAGE $V_{b(i+1)}$ CONNECTED TO THE GATE OF THE ADDITIONAL TRANSISTOR $N(i+1)$.

TEST 3: IF THE NUMBER OF ITERATIONS (i) IS TOO LARGE, (E.G. THE NUMBER OF ADDITIONAL TRANSISTORS IS GREATER THAN PERMISSIBLE, THERE IS NO SOLUTION WITH THE SET OF THE CIRCUIT PERFORMANCE CONSTRAINTS SELECTED) THEN GO TO END, OTHERWISE, GO TO STEP 10.

STEP 10. RE-APPORTION DRAIN-SOURCE VOLTAGE EXTREMA $\{V'(n)_{max}\}$ TO DECREASE THE RESPECTIVE EXCESS VOLTAGE EXTREMA $V(i)_{max}$ ACROSS TRANSISTOR (i) TO $V'(i)_{max}$ (AND TO DECREASE ITS CORRESPONDING EXCESS PEAK SUBSTRATE CURRENT $\{I_{sub(i)max}\}$), AND TO DISTRIBUTE THE BALANCE $V_{outmax} - V'(i)_{max}$ ACROSS THE REMAINING SERIES CONNECTED TRANSISTORS. $N(n-1)$.

STEP 11. COMPUTE A NEW SET OF FIXED BIAS VOLTAGES $\{V_{bi}\}$, E.G. (V_{ref}, V_{bias}, \dots), (E.G., BY THE METHOD OF LAGRANGE MULTIPLIERS) UNDER THE CONSTRAINTS OF THE REQUIREMENT SET $\{R\}$ AND THE REAPPORTIONED DRAIN-SOURCE VOLTAGE EXTREMA $\{V'(n)_{max}\}$ FOUND IN STEP 10. GO TO STEP 3.

END.

An Alternative Circuit Embodiment of the Present Invention

With reference to FIG. 7 there is shown an alternative embodiment of the invention in a current mirror circuit 700. Circuit 700 is a cascode current mirror that can be used as a high impedance output stage of a high gain amplifier stage e.g. the circuit in FIG. 6.

A signal source current, I_s , (e.g., the output V_{out} of FIG. 6) drives an input terminal 701, of the current mirror. Another current source I_o , drives an output terminal V_{out1} , of the current mirror. Both I_s and I_o are sourced from power-supply terminal V_{dd} .

As in other embodiments of the present invention, in the current mirror circuit 700, additional voltage sharing source-drain connected series transistors 702, 704 are arranged in an input series current path L1. The series current path L1 extends from the input terminal 701 through the series

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connected transistors 702, 704 to a drain terminal 705 of upper cascode transistor 710 and continues through series connected lower cascode transistor 712 to V_{ss} (ground). Upper transistor 710 and lower transistor 712 are joined at respective source and drain terminals at a common junction 709.

Also additional voltage sharing source-drain connected series transistors 706, 708 are arranged in an output series current path L2. The series current path L2 extends from the output terminal V_{out1} through the series connected transistors 706, 708 to a drain terminal 707 of upper cascode transistor 714 and continues through series connected lower cascode transistor 716 to V_{ss} (ground). Upper transistor 714 and lower transistor 716 are joined at respective source and drain terminals at a common junction 711.

Corresponding gates of transistors 702, 704 and 706, 708 are biased by fixed voltage sources 722, 724, 726, 728 respectively. Transistors 710, 714 gates are driven from complement (-) and true(+) outputs 730, 734 of a dual op-amp 740. Corresponding inverting, non-inverting inputs 742, 744 of the op-amp 740 are connected to common junctions 709, 711 respectively.

The current mirror circuit 700 provides high output impedance and current gain by the ratio of the size of transistors 716 and 712 as is well known.

Let $Q_c[J]$ refer to the group of the four drain-to-source connected cascode transistors, (two chains of series connected transistors) [710, 712] and [714, 716]. Let $Q_a[K]$ refer to the group of additional drain-to-source series connected transistors (two additional chains of series connected transistors) [702, 704] and [706, 708]. For $1 < j < 2$, transistors $Q_c[j]$ are the cascode (chain) transistors $Q_c[J1]$ in the first series path L1 connecting from an upper drain terminal 705 of the chain $Q_c[J1]$ to V_{ss} . For $3 < j < 4$, transistors $Q_c[j]$ are the cascode (chain) transistors $Q_c[J2]$ in the second series path L2 connecting from an upper drain terminal 707 of the chain $Q_c[J2]$ to V_{ss} . Furthermore, let the respective bias voltages 722, 724, 726, and 728 be represented by $V_b[K]$ corresponding to the $Q_a[K]$ additional series transistors 702, 704, 706, and 708.

For $1 < k < 2$ transistors $Q_a[k]$ are the additional drain-to-source series connected (i.e. chain) transistors $Q_a[K1]$ in the series path L1 connecting from the input node 701 to the upper drain terminal 705 of the first cascode chain $Q_c[J1]$. Similarly, For $3 < k < 4$ transistors $Q_a[k]$ are the additional drain-to-source series (chain) connected transistors $Q_a[K2]$ in the series path L2 connecting from the output node V_{out1} to the upper drain terminal 707 of the cascode chain $Q_c[J2]$.

A limit value for excess substrate current for each transistor $Q_c[j]$ in the chains $Q_c[J1]$ and $Q_c[J2]$ caused by a respective drain-to-source voltage stress $V_{ds[j]}$ can be represented as the respective maximum allowable substrate current $I_{submax(j)}$ for the transistor, $Q[j]$, caused by the corresponding drain-source voltage $V_{ds(j)} = V_{dsmax(j)}$.

In order to stabilize the gain of the circuit 700 from degradation by excessive substrate current (i.e., at $V_{ds(j)} > V_{dsmax(j)}$) due to voltage overstress on the cascode transistors 712, 710 and 714, 714, the biased-stabilizing additional transistors $Q[k]$ e.g. transistors 702, 704 and 706, 708, are selectively biased by respective voltage bias sources $V_b(k)$ e.g. 722, 724 and 726, 728, to limit the respective cascode transistor voltages $V_{ds(j)}$ (i.e. 774, 776, 786, 788) to not exceed a respective maximum $V_{dsmax(j)}$.

The maximum voltage ($V_{ds(j)} = V_{dsmax(j)}$) that will appear across each respective series cascode transistor $Q_c[j]$ depends on the operational conditions under which the circuit 700 is operated. For a given set $\{R\}$ of selected

performance characteristics (e.g. gain and output impedance) and selected operational characteristics [e.g. high and low limits of the input signal (I_{smax} , I_{smin}), selected maximum supply voltage limit VDD_{max} and selected maximum output voltage level, $Vout_{max}$ and maximum output voltage swing (dynamic range, $Vout_{max} - Vout_{min}$)] the bias voltages $Vb(k)$ are selected to limit the drain-to-source voltages $Vds(j)$ of the cascode transistors $Qc(j)$ to be less than the respective maximums $Vds(j)_{max}$, thereby stabilizing the selected circuit performance characteristic(s) for the selected operational characteristic (s).

In general, in a current path through a chain of series connected transistors (e.g. **L1** or **L2**) connected between a source of current, (e.g. node **701** and/or $Vout1$) and ground (e.g. Vss), to ensure that substrate currents $Isub(j)$, for drain-to-source connected cascode transistors ($Qc[j]$) in a cascode portion (e.g. $Qc[J]$) of the chain (**L1**, **L2**) connected between an intermediate drain node (e.g. nodes **705** or **707**) to ground do not exceed selected limits (e.g. $Isub(j)_{max}$), the respective gates of corresponding additional transistors (e.g. $Qa[k]$) in an interposed portion (e.g. $Qa[K]$) of the chain (**L1** or **L2**) coupled between the intermediate drain node (e.g. nodes **705** or **707**) and a respective source of current (e.g. I_o or I_s) are connected to respective bias voltages (e.g. $Vb[k]$) and the bias voltages are selected to limit the respective maximum drain-to-source voltage excursions (e.g. $Vds(j)_{max}$) on the transistors $Qc[J]$ to not exceed a corresponding maximum (e.g. $Vds_{max}(j)$).

In addition, the series connected, voltage-sharing, biased-stabilized transistors **702**, **704** and **706**, **708** may be biased by the respective bias sources **722**, **724** and **726**, **728** to operate from their respective triode regions into their respective saturation regions as the output voltage $Vout1$ swings from maximum output voltage, $Vout1_{max}$ to the minimum output voltage, $Vout1_{min}$.

Thus the circuit **700** is stabilized to retain high output impedance, and a high gain characteristic over a wide output voltage dynamic range while simultaneously eliminating or minimizing gain or output impedance degradation due to excessive substrate current generation from voltage over-stress.

The actual bias voltage values for the respective bias sources **722**, **724** and **726**, **728** are dependent on the particular values for Vdd_{max} , $Vout_{min}$, $Vout_{max}$, I_{smin} and I_{smax} and the particular respective transistor width ($We(i)$), length ($Le(i)$) and width-to-length ratio ($We(i)/Le(i)$) considered, where (i) represents the transistors $Qc(j)$ and $Qa(k)$. Solution for the bias voltage values $Vb(k)$ for the respective bias sources **722**, **724** and **726**, **728** then becomes a circuit simulation and transistor modelling analysis problem, e.g. as that shown in the references described above.

Solution methods are known for solving such conditionally constrained problems. For example, the circuit **700** may be represented as a linear circuit graph or schematic (not shown) using known linear circuit models for the transistors $Qc(j)$ and $Qa(k)$. A set of loop or node equations (not shown) can be written and solved by matrix methods to determine respective node voltages and loop currents for the circuit **700** linear circuit schematic. A corresponding set of related polynomial equations can be derived from the set of loop and node equations incorporating the selected operational and performance limits. Application of known mathematical techniques, such as the method of LaGrange polynomials can be used to determine the desired set of $Vb(k)$ bias voltages for achieving the selected operational and performance characteristics for the circuit **700**.

Suitable selection of the bias values $Vb(k)$ for the respective bias sources **722**, **724** and **726**, **728** to limit substrate currents to less than the excess limits thus ensures that the selected characteristic (gain, output resistance) of the current mirror circuit **700** is stabilized over the expected operating supply voltage and input signal levels.

It will be apparent to skilled practitioners of electrical circuit design and modelling, by application of the techniques shown in the present circuit characteristic stabilizing invention, that more than just the two cascode transistors **710** and **712** or **714** and **716** may be protected from excessive drain-to-source voltages. By suitable addition of more than two series drain-source connected transistors $Qa(k)$ in a current path **L1** or **L2** and by suitable selection of bias voltages $Vb(k)$, other transistors, specifically transistors selected from the group of the additional drain-source connected transistor $Qa(k)$ may also be protected from excessive drain-to-source voltage $Vds(k)$.

Although the reduced hot electron effect, performance stabilizing cascode circuit invention has been described for a single-well n-channel CMOS process, it is apparent that embodiments of the substrate current-bias stabilizing circuit invention may be implemented using transistors fabricated by a single-well p-channel or a dual-well CMOS process by appropriate changes in voltage polarity and current flow.

What is claimed is:

1. A cascode circuit comprising:

- a first transistor having respective source, drain and gate terminal, said first transistor gate terminal coupled to an input signal referenced to a first power supply and said first transistor source terminal coupled to said first power supply;
- a second transistor having respective source, drain and gate terminal;
- said second transistor source terminal and said first transistor drain terminal coupled to form a first source-drain connection;
- a first cascode circuit output terminal coupled to a second power supply voltage;
- first circuit means for biasing said second transistor gate terminal with respect to said first power supply such that said first transistor operates in a saturation operating region; and
- a voltage limiting circuit interposed between said first output terminal and said second transistor drain adapted to limit a respective first drain-to-source voltage across said first transistor and a respective second drain-to-source voltage across said second transistor not to exceed a corresponding first maximum drain-to-source voltage limit and a corresponding second maximum drain-to-source voltage limit, the voltage limiting circuit comprising a third transistor having respective source, drain and gate terminals, said third transistor drain being coupled to said output terminal, said third transistor source being coupled to said second transistor drain and said third transistor gate being coupled to a selected, substantially fixed voltage.

2. The cascode circuit according to claim 1, wherein said selected, substantially fixed voltage is selected to limit said first transistor drain-to-source voltage and said second transistor drain-to-source voltage to not exceed said respective maximum drain-to-source voltage limits.

3. The cascode circuit according to claim 1, in which said selected, substantially fixed voltage is said second power supply terminal.

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4. A cascode circuit comprising:

- a first transistor having respective source, drain and gate terminals, said first transistor gate terminal coupled to an input signal referenced to a first power supply and said first transistor source terminal coupled to said first power supply;
- a second transistor having respective source, drain and gate terminals;
- said second transistor source terminal and said first transistor drain terminal coupled to form a first source-drain connection;
- a cascode circuit output terminal coupled to a second power supply voltage;
- first circuit means for biasing said second transistor gate terminal with respect to said first power supply such that said first transistor operates in a saturation operating region; and
- a voltage limiting circuit interposed between said first output terminal and said second transistor drain adapted to limit a respective first drain-to-source voltage across said first transistor and a respective second drain-to-source voltage across said second transistor not to exceed a corresponding first maximum drain-to-source voltage limit and a corresponding second maximum drain-to-source voltage limit, the voltage limiting circuit comprising:
 - a first additional transistor having respective drain, gate and source terminals;
 - a second additional transistor having respective drain, gate and source terminals;
 - said second additional transistor drain terminal being coupled to said output terminal;
 - said second additional transistor source terminal being coupled to said first additional transistor drain terminal;
 - said first additional transistor source terminal being coupled to said first transistor drain terminal;
 - said first additional transistor gate being adapted to couple to a selected first substantially fixed voltage; and
 - said second additional transistor gate being adapted to couple to a selected second substantially fixed voltage.

5. The cascode circuit according to claim 4, wherein said first substantially fixed voltage and said second substantially fixed voltage are selected so that said first transistor drain-to-source voltage and said second transistor drain-to-source voltage do not exceed said respective maximum drain-to-source voltage values.

6. The cascode circuit according to claim 5, wherein one of said selected first and second substantially fixed voltages is adapted to be coupled to said second power supply terminal.

7. A cascode circuit comprising:

- a first transistor having respective source, drain and gate terminals, said first transistor gate terminal coupled to an input signal referenced to a first power supply and said first transistor source terminal coupled to said first power supply;
- a second transistor having respective source, drain and gate terminals;
- said second transistor source terminal and said first transistor drain terminal coupled to form a first source-drain connection;
- a cascode circuit output terminal coupled to a second power supply voltage;
- first circuit means for biasing said second transistor gate terminal with respect to said first power supply such

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that said first transistor operates in a saturation operating region; and

- a voltage limiting circuit interposed between said first output terminal and said second transistor drain adapted to limit a respective first drain-to-source voltage across said first transistor and a respective second drain-to-source voltage across said second transistor not to exceed a corresponding first maximum drain-to-source voltage limit and a corresponding second maximum drain-to-source voltage limit, the voltage limiting circuit comprising:
 - a plurality of additional individual transistors each having respective individual drain, gate and source terminals, said plurality of additional individual transistors interposed in serial source-drain connection between said output terminal and second transistor drain terminal; and
 - each respective gate of said plurality of additional individual transistors being adapted to be coupled to a corresponding substantially fixed voltage source, each one of said corresponding fixed voltages being selected to co-operate with said voltage limiting circuit,
- whereby said first transistor drain-to-source voltage and said second transistor drain-to-source voltage do not exceed said respective first and said second maximum drain-to-source voltage limits.

8. A cascode circuit comprising:

- a first transistor having respective source, drain and gate terminals, said first transistor gate terminal coupled to an input signal referenced to a first power supply and said first transistor source terminal coupled to said first power supply;
- a second transistor having respective source, drain and gate terminals;
- said second transistor source terminal and said first transistor drain terminal coupled to form a first source-drain connection;
- a cascode circuit output terminal coupled to a second power supply voltage;
- first circuit means for biasing said second transistor gate terminal with respect to said first power supply such that said first transistor operates in a saturation operating region; and
- a voltage limiting circuit interposed between said first output terminal and said second transistor drain adapted to limit a respective first drain-to-source voltage across said first transistor and a respective second drain-to-source voltage across said second transistor not to exceed a corresponding first maximum drain-to-source voltage limit and a corresponding second maximum drain-to-source voltage limit, the voltage limiting circuit comprising at least one additional transistor having respective source, drain and gate terminals, said drain of said at least one additional transistor being coupled to said output terminal, said source of said at least one additional transistor being coupled to said drain of said second transistor and said gate of said at least one additional transistor being coupled to a selected substantially fixed voltage, said selected substantially fixed voltage cooperating with said circuit,
- wherein said first transistor, said second transistor, said coupling to said second power supply, said first circuit means for biasing, said first drain-to-source voltage and said second drain-to-source voltage are selected such that said cascode circuit defines a circuit performance

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characteristic that provides maximum drain-to-source voltage values.

9. The cascode circuit according to claim 8, wherein said selected substantially fixed voltage is said second power supply terminal.

10. The cascode circuit according to claim 8, wherein said voltage limiting circuit comprises:

drain-source series connected first and second additional transistors having respective drain, gate and source terminals, said drain-source series being connected to first and second additional transistors interposed between said output terminal and said second transistor drain terminal;

a selected first substantially fixed voltage coupled to said first additional transistor gate;

a selected second substantially fixed voltage coupled to said second additional transistor gate; and

said selected first substantially fixed voltage and said selected second substantially fixed voltage being selected such that said cascode circuit exhibits said performance characteristic limit.

11. The cascode circuit according to claim 10, wherein said second power supply terminal is at least one of said selected first and second substantially fixed voltages.

12. The cascode circuit according to claim 10, comprising;

a selected length, L_e , and width, W_e , for a respective one of said transistors, said selected length, L_e and width, W_e , selected to co-operate with said voltage limiting circuit to establish a respective limit value for a corresponding circuit operational characteristic, where said respective limit value and said corresponding circuit operational characteristic comprises at least one of the following:

a maximum limit value for said second power-supply voltage;

an upper input voltage limit for said input signal;

a lower input voltage limit for said input signal;

an upper output voltage limit for said output terminal;

a lower output voltage limit for said output terminal;

a bias voltage limit for said V_{bias} voltage; and

a reference voltage limit for said reference voltage.

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13. The cascode circuit according to claim 10, wherein said cascode circuit is operated within voltage operating limits selected from the group of maximum cascode output voltage, minimum cascode circuit output voltage, maximum input terminal voltage and maximum input terminal voltage.

14. A cascode circuit comprising:

a first transistor having respective source, drain and gate terminals, said first transistor gate terminal coupled to an input signal referenced to a first power supply and said first transistor source terminal coupled to said first power supply;

a second transistor having respective source, drain and gate terminals;

said second transistor source terminal and said first transistor drain terminal coupled to form a first source-drain connection;

a cascode circuit output terminal coupled to a second power supply voltage;

first circuit means for biasing said second transistor gate terminal with respect to said first power supply such that said first transistor operates in a saturation operating region, said first circuit means comprising a differential amplifier that comprises:

an inverting input coupled to said first source-drain connection;

a non-inverting input coupled to a substantially fixed reference voltage; and

an amplifier output terminal responsive to a voltage difference between said inverting input and said non-inverting input, in which said amplifier output terminal is coupled to said gate of said second transistor; and

a voltage limiting circuit interposed between said first output terminal and said second transistor drain adapted to limit a respective first drain-to-source voltage across said first transistor and a respective second drain-to-source voltage across said second transistor not to exceed a corresponding first maximum drain-to-source voltage limit and a corresponding second maximum drain-to-source voltage limit.

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